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Automated detection of hidden internal insect infestations in wheat kernels using electrical conductance

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Abstract. *The wheat industry is in need of an automated, economical, and rapid means to detect whole wheat kernels internally infested with insects. The feasibility of the Perten Single-Kernel Characterization System (SKCS) to detect internal insect infestations was studied. The SKCS monitors compression force and electrical conductance as individual kernels are being crushed. Samples of hard red winter wheat (HRW) and soft red winter wheat (SRW) infested with rice weevil and lesser grain borer were run through the SKCS and the conductance/crush signals saved for post-run processing. It was found that a discontinuity is often present in the conductance signal of an insect-infested kernel. An algorithm was developed to classify kernels as infested, based on features of the conductance signal. Average classification accuracies for all wheat samples were 24.5% for small-sized larvae, 62.2% for medium-sized larvae, 87.5% for large-sized larvae, and 88.6% for pupae. There were no false positives (sound kernels classified as infested). The classification algorithm is robust for a wide range of moisture contents. Classification accuracy was somewhat better for kernels infested with rice weevils than for lesser grain borer, and classification accuracy was better for HRW than for SRW.*

Keywords: rice weevil, lesser grain borer, SKCS, conductance

Introduction

Internal insect infestation of wheat kernels degrades quality and value of wheat and is one of the most difficult defects to detect. Insect infestation causes grain loss by consumption, contaminates the grain with excrement and fragments, causes nutritional losses, and degrades end-use quality of flour (Sanchez-Marinez et al., 1997; Pederson, 1992). Stored grain is vulnerable to both external and internal damage by insects, but internal infestations are the most difficult to detect and are generally considered the most damaging (Pederson, 1992). There are five species of insects where the larval and pupal stages develop inside wheat kernels for four to seven weeks, without any visible indication, until they mature and emerge from the kernel via an exit tunnel. These are the rice weevil [*Sitophilus oryzae* (L.)], maize weevil [*Sitophilus zeamais* (Motsch)], granary weevil [*Sitophilus granarius* (L.)], lesser grain borer [*Rhyzopertha dominica* (F.)], and angoumois grain moth [*Sitotroga cerealella* (Olivier)]. Infestations from the angoumois grain moth are usually limited to the top few inches in the bin of stored grain, while the other insects can infect grain in pockets anywhere in the bin. Weevils and lesser grain borer insects have been identified as the most common internal infesters of wheat (Storey et al., 1982).

U.S. Wheat Standards consider kernels as insect damaged when exit tunnels or boring are observed on the kernel surface (Federal Grain Inspection Service, 1997). However, internal insects have already emerged from these kernels. A wheat load is reduced to U.S. Sample Grade if 32 or more insect-damaged kernels are found in 100 grams of wheat (Federal Grain Inspection Service, 1997). Inspecting for insect-damaged kernels is labor intensive and may miss many infested kernels where an immature insect has not emerged from the kernel. Storey et al. (1982) reported that as many as 12% of all wheat samples from export loads have hidden internal insects but go undetected during the normal grain inspection process. Grain inspectors at milling facilities need to know the quantity of hidden insect damage so that loads with excessive infestations can be cleaned or diverted for other uses.

Several methods have been or are currently under development to detect hidden insects in whole wheat kernels. Pederson (1992) reviewed many of the techniques for detecting internal insects. These include staining the egg plug to detect weevil infestation, flotation methods, x-ray imaging, acoustic detection of larvae movement and chewing, carbon dioxide measurement, and staining of amino acids specific to insect body fluids. However, most of these methods have only achieved limited implementation either because they are slow, labor intensive, expensive, or can only detect specific insect species. In more recent work, Haff (2001) developed an image analysis program to automatically scan x-ray images for insect infestation. Other researchers have investigated use of near-infrared (NIR) spectroscopy to detect hidden insects in wheat kernels (Dowell et al., 1998; Ridgway and Chambers, 1996; Ghaedian and Wehling, 1997). Both x-ray and NIR spectroscopy can detect internal insects with high accuracy and cost of the required equipment has fallen in the past few years. However, x-ray and NIR instrumentation are still cost prohibitive for many commercial applications, and current NIR instrumentation requires complex procedures and calibrations. Thus, no economically viable and simple equipment utilizing these technologies has yet become available for grain inspectors to use to detect internal insects.

The single-grain characterization system (SKCS) (SKCS 4100, Perten Instruments, Springfield, IL) measures kernel weight, moisture content, diameter, and hardness at a rate of two kernels per second, and reports the average and standard deviation of a 300-kernel sample. These systems are used worldwide in many inspection facilities to determine wheat physical properties. To measure moisture content and hardness, electrical conductance and compression force are monitored and stored by the SKCS, while a kernel is being crushed between a wheel and crescent (Martin et al., 1993). Since an insect has a much higher moisture than normal wheat kernels, it may be that the presence of internal insects can be detected through processing of the conductance signal during crushing. The objective of this study is to determine the feasibility of detecting live, internal insects with the standard hardware of the SKCS.

Experimental Procedures

Insect rearing and maturity estimation

Two species of insects, rice weevils [*Sitophilus oryza* (L.)] and lesser grain borer [*Rhyzopertha dominica* (F.)], were reared with two different wheat classes, hard red winter (HRW) and soft red winter (SRW), for a total of four insect-wheat class combinations. The HRW was grown in central Kansas and harvested in 2000, while the SRW was grown in Ohio and harvested in 1994. Both stocks of wheat were stored at 10 °C after harvest. Insect rearing was performed in quart-sized jars with screen lids, with approximately 350 g of wheat and 300 adult insects. The jars were incubated at 26 °C and 60% RH. Insect rearing for each insect-wheat class combination was performed at different times. Starting at the second week after incubation began, approximately 1500 kernels were removed on a weekly basis until the end of the sixth week. These samples were radiographed using a cabinet x-ray system (Faxitron Corp, #43855A, Wheeling, IL), using 13 x 18 cm film (Kodak Industry M film, France), at an exposure of 18 kVp and 3 mA for two minutes. Observation of these films under a microscope allowed segregation of infested from non-infested (sound) kernels. Approximately 300 of the infested kernels were set aside and placed on thin plastic sheets, secured with double-stick tape, and radiographed again for maturity estimation. To determine insect maturity, this x-ray film was digitally scanned at 800 pixels/inch (Expression 1680, Epson America, Long Beach, CA), and the larvae cross-sectional area was measured in an image-editing program (Adobe Photoshop LE 5.0, Adobe systems, San Jose, CA). Kernels were assigned to one of five categories, as listed below, based on the insect larvae size and/or insect morphology:

1. Sound: no insect present
2. Small larvae: larvae area approximately 0.20 to 0.7 mm^2
3. Medium larvae: larvae area approximately 0.9 to 1.4 mm^2
4. Large larvae: larvae area approximately 1.6 to 2.8 mm^2
5. Pupae: pupae area approximately 1.6 mm^2 or larger with limbs, snout, and/or wing features visible

For rice weevils, the small larvae approximately corresponds to the first and second larval instar stage, while the medium and large larvae correspond to the 3^{rd} and 4^{th} larval instar stage, respectively (Kirkpatrick and Wilbur, 1965). The lesser grain borer is a smaller insect than the rice weevil. Thus, within each size category the lesser grain borers are likely more mature than the rice weevils; thus, the categories of small, medium, and large larvae would likely refer to a more mature insect for lesser grain borer than rice weevil.

The number of kernels used for the study from all combinations of insect and wheat class are listed in Table 1. The sound kernels had a mean moisture content (MC) of 12.1% (wet basis), with a standard deviation (SD) of 0.87%. Normally, non-infested kernels removed from one homogenous load would have an MC standard deviation of about 0.3 to 0.4%. The large SD for the sound kernels in this study is at least in part due to kernels being removed and MC measured over the three-month duration of the study. In addition to these sound kernels, sets of 25 HRW kernels and SRW kernels were hydrated up to 14%, 16%, 18%, and 20% MC (wet basis) to determine if insect-infested kernels could be distinguished from very moist kernels. These kernels were tempered by sufficient quantities of water to raise the MC to the desired level. The sample was stored over 24 hours to allow moisture to equilibrate.

Table 1. Number of kernels used from each insect – wheat class combination.

Insect maturity	rice weevil-HRW	rice weevil- SRW	lesser grain borer - HRW	lesser grain borer - SRW
Small larvae	113	101	106	112
Medium larvae	111	101	103	104
Large larvae	122	110	105	125
Pupae	113	109	106	129
Sound	343	352	350	340

Note: HRW = Hard Red Winter Wheat; SRW = Soft Red Winter Wheat

Conductance measurement

After insect maturity was determined, kernels were processed with the SKCS in sets of 20 to 40 kernels. Normal moisture and hardness data that the SKCS automatically computes was saved for analysis. Additionally, the SKCS software was set to save the conductance and crush signals of each kernel for off-line analysis. In the SKCS, a kernel acts as one resistor in a two-resistor voltage divider circuit (Martin et al., 1993). Conductance is monitored by measuring the voltage across the kernel. A low-voltage measurement corresponds to low-kernel resistance, which is typical of high-MC kernels. The SKCS digitizes the voltage across the kernel at a rate of 4000 Hz while the kernel is being crushed, but only every 5th data point is actually stored. Data acquisition is triggered by the compression force exceeding a factory-set threshold. A kernel remains between the crescent and wheel of the SKCS for approximately 150 ms while it is being crushed, so each conductance signal contained 135 to 140 points.

Processing of conductance signals

If a live insect is present inside a kernel, there will likely be a large downward slope in the conductance signal. This is likely caused by high-moisture insect parts and fluid coming into contact with the crushing wheel or crescent and drastically lowering its resistance. Occasionally, a dry non-infested kernel will have a sharp peak in its conductance signal that will include a downward slope of similar magnitude caused by insects. However, these slopes always occur at levels greater than the initial voltage level across the kernel. This can be seen in Figure 1, which displays typical conductance signals from several types of kernels. Furthermore, the range of voltage levels in the conductance signal, when computed as the difference of the initial voltage level from the minimum voltage level, will be low for sound kernels of all moisture levels and much higher for kernels infested with insects. Thus, a program was written to read all stored conductance signals, and compute the maximum downward gradient value and the range of voltages. Gradient was computed using equation 1 and voltage range computed using equation 2.

$$Gradient = \begin{cases} V_x - V_{x+1} \text{ if } V_x < V_0 \\ 0 \text{ if } V_x \geq V_0 \end{cases} \qquad (1)$$

$$Range = V_0 - V_{min} \qquad (2)$$

V_0 and V_{min} are the initial and minimum voltages measured across the kernel, respectively; and V_x, V_{x+1} are the voltages of sampled points *x* and *x+1,* respectively. When V_x was greater than V_o, the gradient values were set to zero since these gradients would be in peaks in the conductance signal due to dry kernels.

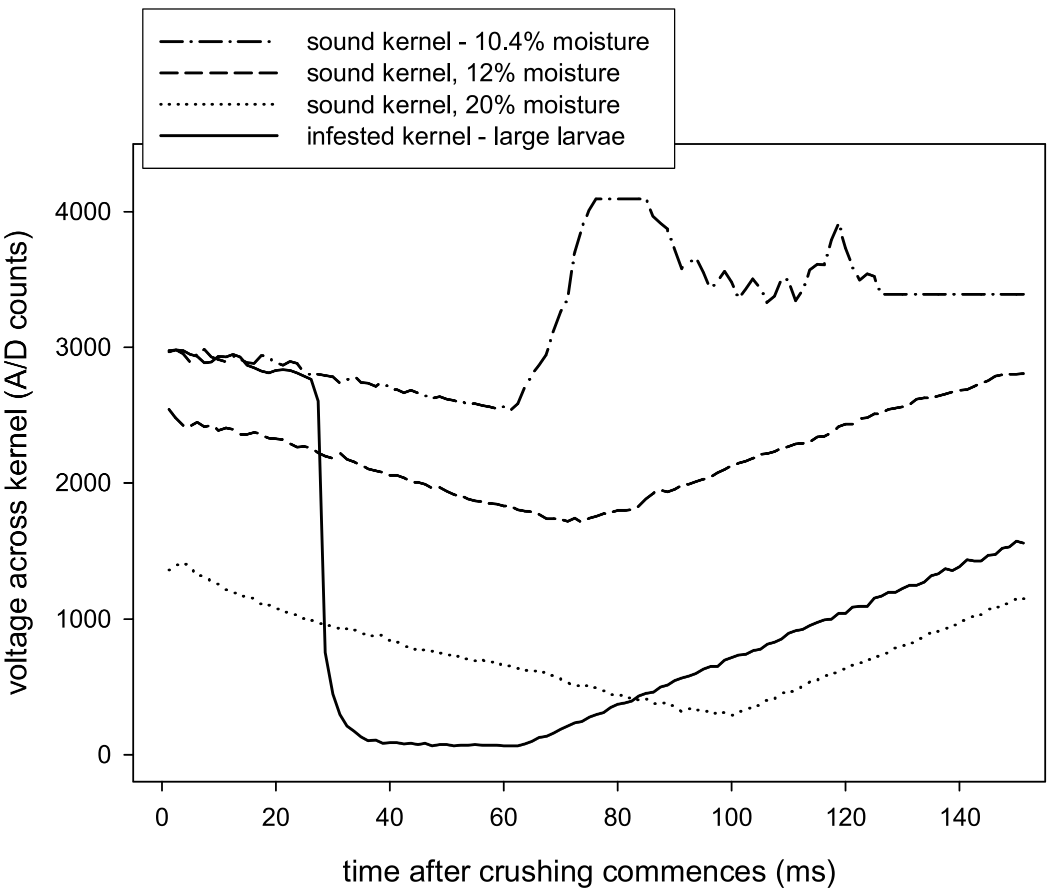

Figure 1. Typical conductance signals as kernels are being crushed in the SKCS 4100.

Results and Discussion

Classification from conductance signal features

Figure 2 displays a scatter plot of all maximum gradient values and voltage ranges in the conductance signals from all kernels. The ellipse with a solid boundary is a 99.90% prediction interval for sound kernels of all MCs. Since it is important to minimize false-positive errors (sound kernels classified as infested), a 99.99% prediction ellipse was computed and all data points falling outside this ellipse were classified as insect infested. There were no false-positive errors made using this classification scheme with the data collected; however, a false-positive classification error of 0.01% might be expected. Classification results for each insect–wheat class combination are shown in Figure 3. Higher classification accuracy is obtained for more mature insects. This is expected given the insect size increases with maturity. Average classification accuracy for all infested kernels from both wheat classes were 24.5% for small larvae, 62.2% for medium larvae, 87.5% for large larvae, and 88.6% for pupae. The best classification results were obtained for HRW infested with rice weevils. Generally, HRW had better classification results than SRW, and more rice weevil infestations were detected than lesser grain borer infestations. Rice weevils are a larger insect than lesser grain borers and that may have been a factor for their higher detection rate. Additionally, HRW may break apart more suddenly than SRW, causing insect fluids to contact the SKCS wheel or crescent more abruptly, leading to larger gradients in the conductance signals. However, more study would be needed to confirm if the differences in detection accuracies between wheat classes and insect species are indeed significant. Table 2 summarizes the values of conductance signal voltage range and maximum gradient found for all the sample sets used in this study. Analysis of variance found that wheat class, wheat moisture, and insect species did not cause any means for maximum gradient or voltage range to be significantly different at the 95% confidence level. Means of tempered sound kernels with high MCs were not significantly different than means of sound kernels that were pulled from the incubation jars. Only insect maturity caused significantly different means. In all cases, kernels infested with insects past the small larval stage had significantly different means than sound kernels at the 95% confidence level. Kernels infested with small larvae did not have significantly different means than sound kernels at the 95% confidence level.

Classification results obtained from the SKCS data compare favorably with x-ray imaging and near-infrared spectroscopy methods used to detect internal insects. Human examination of x-ray films has a higher detection accuracy for infested kernels at all maturity levels but can have false-positive errors of 1.0% or higher (Haff, 2001). Computer algorithms to automatically scan x-ray images have similar recognition rates as the SKCS for insect-infested kernels but have higher false-positive rates, about 7.4% (Haff, 2001). Near-infrared spectroscopy methods also suffer from false positive errors and, additionally, kernel orientation problems (Ghaedian and Wehling, 1997). Both x-ray imaging and near-infrared spectroscopy methods have the advantage that the insect does not need to be alive in order to be detected, and these methods are non-destructive. Future work will be conducted to determine the ability of the SKCS to detect insect infestations where the insects are dead and dried out.

Classification from moisture data alone

Kernels containing internal insects tend to have higher MC's than adjacent sound kernels. The mean MC of all sound kernels used in this study was 12.1% (wet basis), with a standard deviation of 0.87%. These were kernels held in the incubation jars which did not become infested. Moisture contents of infested kernels were generally higher, as listed in Table 3 and graphically shown in Figure 4. Kernels were classified as infested if their MC exceeded the sound kernel mean plus three times the SD (14.7%). This method yields fairly good classification results, as listed in Table 4. However, this method was not as accurate as using the maximum downward gradient and range of voltages in the conductance signals. Furthermore, using MC alone may lead to false-positive errors if high-moisture kernels happen to be present in the sample.

Classification results using moisture data alone might be improved by using the mean and standard deviation from the actual sample being tested. Large samples of sound kernels (above 300 kernels) drawn from a homogenous load would normally have MC standard deviations below 0.4%, even if a small number of infested kernels are present. Using the sample moisture means and standard deviations of kernels infested with insects, listed in Table 3, a prediction of classification accuracy can be made when a normal distribution of kernel MC is assumed. For example, consider a hypothetical case where a sample of kernels has a mean MC of 12.5%, with a standard deviation of 0.4%. Kernels could be classified as infested, with 99.9% confidence, if a kernel with an MC above 13.7% was detected. If this were the case, then infested-kernel detection accuracy would be approximately 29% for kernels infested with small larvae, 61% for kernels infested with medium-sized larvae, 80% for kernels infested with large-sized larvae, and 90% for kernels infested with pupae. A false-positive rate of 0.1% would also be expected.

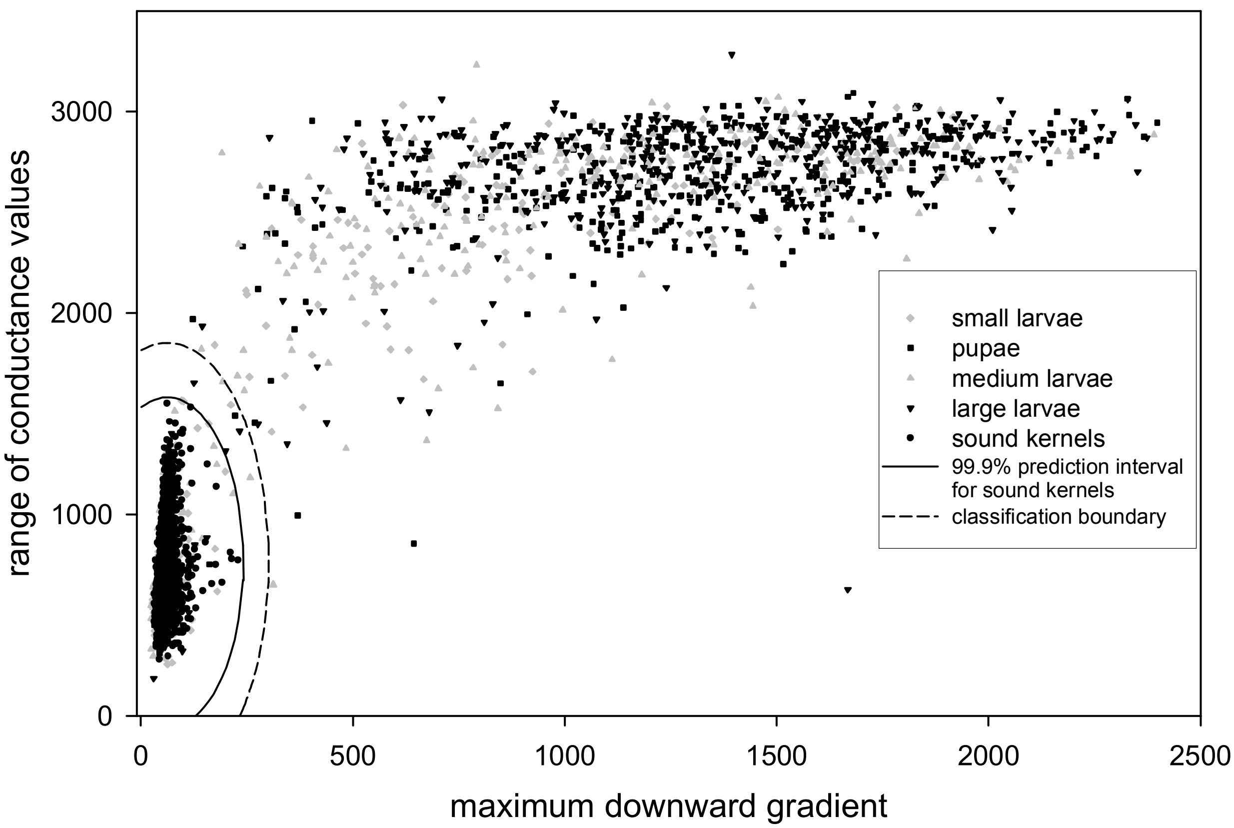

Figure 2. Scatter plot of maximum downward gradient and range of voltages in conductance signals from all kernels.

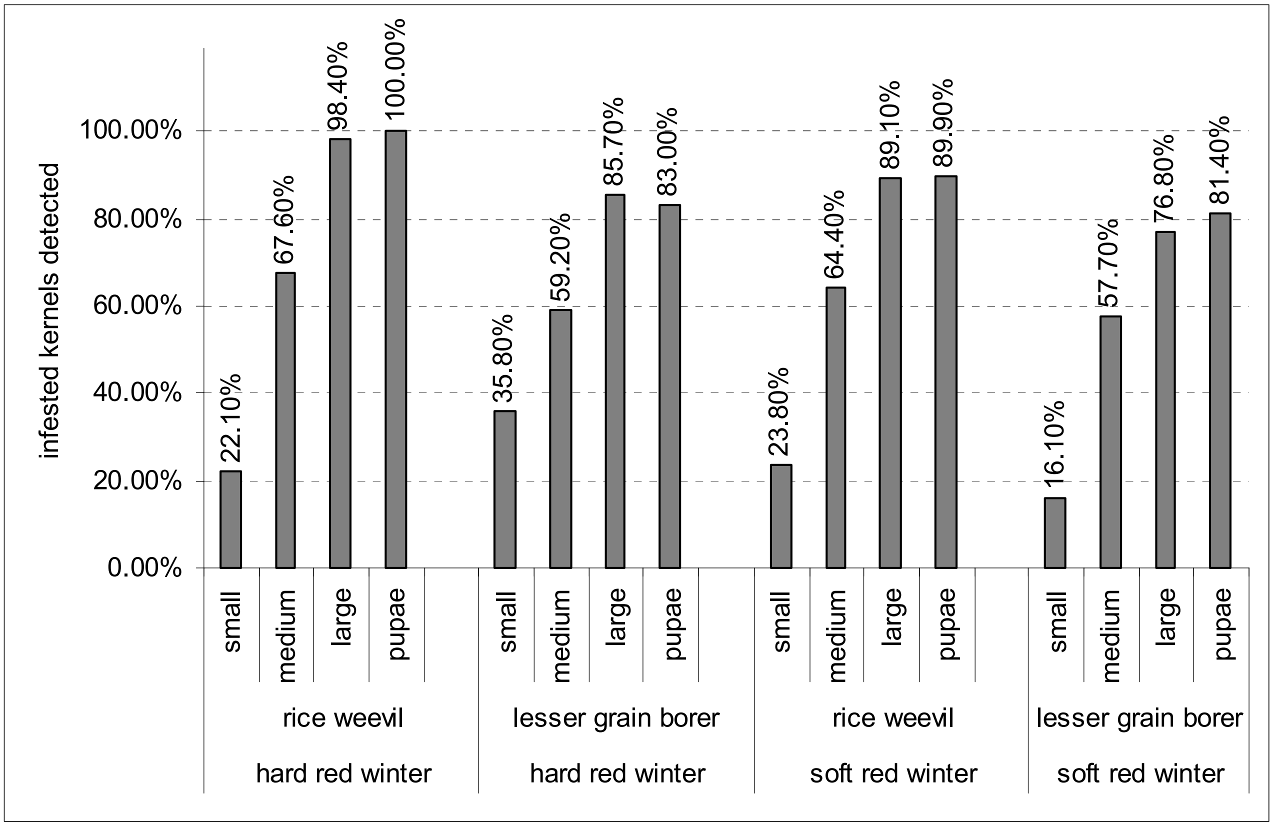

Figure 3. Classification results from all insect maturity, insect species, and wheat class combinations.

Table 3. Moisture contents of infested kernels.

Insect maturity	Moisture content Mean	Moisture content Std dev	Percent kernels classified as infested
Sound	12.07	0.87	0.0
Small larvae	12.52	2.09	15.0
Medium larvae	14.51	2.82	45.5
Large larvae	15.90	2.62	72.0
Pupae	16.63	2.29	81.7

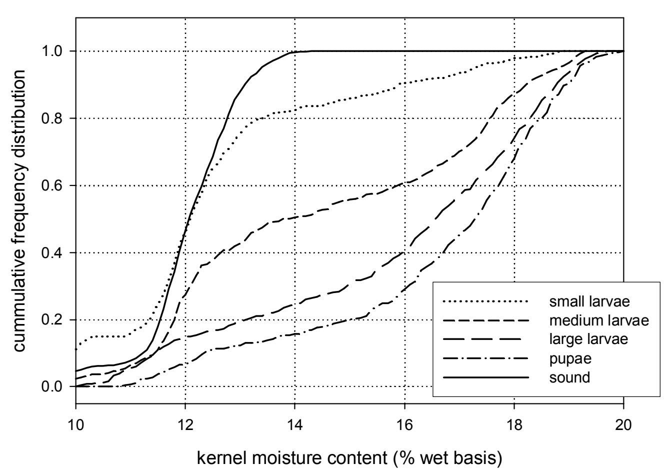

Figure 4. Cumulative frequency distribution of kernel moisture.

Table 2. Summary of conductance signal data.

wheat class	insect	insect maturity	maximum gradient A/D counts mean	maximum gradient A/D counts std. dev.	voltage range A/D counts mean	voltage range A/D counts std. dev.	N
hard	rice weevil	sound	74 a	26	860 a	233	343
hard	rice weevil	small	243 b	372	1102 a	738	113
hard	rice weevil	medium	787 cd	669	2019 bc	893	111
hard	rice weevil	large	1268 e	433	2577 c	246	122
hard	rice weevil	pupae	1151 e	402	2516 c	248	113
hard	lesser grain borer	sound	61 a	10	912 a	181	348
hard	lesser grain borer	small	342 b	430	1389 a	808	106
hard	lesser grain borer	medium	596 c	573	1877 b	808	103
hard	lesser grain borer	large	1182 e	647	2477 c	779	105
hard	lesser grain borer	pupae	910 d	567	2309 c	645	106
soft	rice weevil	sound	56 a	13	662 a	147	352
soft	rice weevil	small	268 b	456	1092 a	828	101
soft	rice weevil	medium	860 d	720	1999 bc	1043	101
soft	rice weevil	large	1226 e	602	2562 c	707	110
soft	rice weevil	pupae	1221 e	551	2493 c	644	109
soft	lesser grain borer	sound	61 a	17	611 a	116	340
soft	lesser grain borer	small	205 ba	381	920 a	674	112
soft	lesser grain borer	medium	757 cd	706	1707 b	1046	104
soft	lesser grain borer	large	1133 e	727	2261 c	1012	125
soft	lesser grain borer	pupae	1197 e	701	2387 c	926	129
hard 14% MC	n/a	sound	57 a	13	868 a	123	25
hard 16% MC	n/a	sound	58 a	16	765 a	246	25
hard 18% MC	n/a	sound	68 a	59	631 a	324	25
hard 20% MC	n/a	sound	71 a	43	865 a	370	25
soft 14% MC	n/a	sound	68 a	23	871 a	352	25
soft 16% MC	n/a	sound	55 a	11	811 a	175	25
soft 18% MC	n/a	sound	55 a	14	754 a	153	25
soft 20% MC	n/a	sound	71 a	43	865 a	370	25

Note: Means within each column denoted with a different letter are significantly different at the 95% confidence level.

Conclusion

The method developed for detecting wheat kernels with internal insects is quite suitable for addition to the measurements currently made by the SKCS 4100. The algorithm employed is the same for all combinations of insect and wheat classes studied. While insect detection rates of the method are not as high as inspection of x-ray films with a magnifying glass, it is comparable to, or better than, other automatic detection methods that exist, and does not suffer from false-positive results. This holds true under all reasonable moisture contents of wheat being inspected. The method developed only detects kernels with live internal insects. More research is needed to determine the feasibility of using the SKCS to inspect grain that has been fumigated, causing the insects to die and lose their moisture content.

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This article reports results of research only. Mention of a proprietary product does not constitute an endorsement or a recommendation by the USDA for its use.

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